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14. ABSTRACT
Given remote and direct physical measurements of a realistic ocean wave-field, we obtain a high-resolution deterministic description of the nonlinear wave-field by integrating the measurements with a phase-resolved wave prediction model including realistic environmental effects such as wind forcing and wave breaking dissipation. The effectiveness of the phase-resolved wave reconstruction and forecasting capability is verified by direct comparisons with HiRes hybrid (radar, ATM and buoy) measurements of realistic ocean wave-fields. In addition, we address the validity, accuracy and limitations of such wave-field reconstruction and forecasting.

15. SUBJECT TERMS
Ocean surface waves, deterministic wave-field reconstruction and forecasting, nonlinear wave-field evolution, phase-resolved wave-field simulation

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High-Resolution Measurement-Based Phase-Resolved Prediction of Ocean Wavefields

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LONG-TERM GOAL

Given remote and direct physical measurements of a realistic ocean wavefield, obtain a high-resolution description of the wavefield by integrating the measurements with phase-resolved wave prediction model including realistic environmental effects such as wind forcing and wave breaking dissipation. Inform and guide the measurements necessary for achieving this reconstruction and address the validity, accuracy and limitations of such wavefield reconstructions.

OBJECTIVES

The specific scientific and technical objectives are to obtain:

1. Development of a phase-resolved, deterministic prediction capability for nonlinear wavefield reconstruction and evolution at intermediate scale (O(1) ~ O(10)km per dimension) using ship-mounted radar wave measurements
2. Incorporation and evaluation of physics-based wind-forcing and wave-breaking models that are developed/calibrated/validated based on simulations and measurements
3. Characterization and quantification of uncertainty and incompleteness in wave sensing and sensed data
4. Direct comparison between quantitative (point and area) field measurements and phase-resolved wavefield reconstruction and forecasting
5. Development of a theoretical/computational framework for guiding the deployment of wave sensing systems and data interpretation

APPROACH

We develop and apply a comprehensive deterministic model for intermediate scale (up to O(10)km per dimension) ocean wave prediction by integrating whole-field and multiple-point measurements of the wave environment with simulation-based wavefield reconstruction. The wave reconstruction is based on phase-resolved **s**imulation of **n**onlinear **o**cean **w**ave (SNOW) dynamics, and utilizes hybrid (from different types of sensors) wave measurements. The simulations also incorporate physics-based wind forcing and wave-breaking dissipation models, which are developed/validated/calibrated based on field/laboratory measurements.

Nonlinear wavefield reconstruction is based on an iterative optimization approach using multilevel phase-resolved wave models of different nonlinearity orders. Specifically, for low-level optimization sufficient for mild waves, the linear and second-order Stokes solutions are used. For high-level optimization necessary for steep waves, an efficient nonlinear wave simulation model (SNOW) based on a high-order spectral method is employed. Once the wavefield is reconstructed, its future evolution is given by the wave propagation model using the reconstructed wavefield as the initial condition (Wu 2004; Yue 2008). In wave modeling, wind forcing is included through a pressure forcing on the free surface, and wave-breaking dissipation is considered by applying an effective low-pass filter to the wave elevation and surface potential in the spectral space. Other physical effects such as those of current and finite depth are also directly considered in wave modeling.

WORK COMPLETED

We focus on the development, validation and performance tests of the phase-resolved nonlinear wave reconstruction and forecasting capability using HiRes field measurements of realistic ocean waves. Specifically,

- **Development of high-resolution wave reconstruction and prediction capability:** We extend the wave reconstruction capability for discrete point wave data to include the presence of radar and ATM sensed wave data. In particular, we develop an understanding of wavefield's predictability (in spatial-temporal domain) based on hybrid (buoy, radar and ATM) sensed wave data.
- **Characterization/quantification of the effects of noise, uncertainty, and incompleteness in sensed wave data on wave reconstruction/prediction:** We develop an approach based on the use of the phase-resolved nonlinear wave reconstruction/prediction to recover the wave information in the shadow of radar measurements and to evaluate the validity and accuracy of wave reconstruction due to the effects of noise, uncertainty, and incompleteness in sensed data.
- **Modeling of wind input:** To account for wind effects in wave reconstruction/prediction, we develop and validate a first generation model for wind forcing input for direct phase-resolved nonlinear wavefield simulations. In this model, the wind forcing is modeled as a pressure distribution closely correlated to wave slope with the growth rate determined by matching to existing laboratory/field observations.
- **Validation and calibration with field measurement:** We conduct various validations and performance tests of the developed wave reconstruction/prediction capability by using HiRes field measurements of realistic ocean waves:

- We use instantaneous and continuous (SPROUL- and FLIP-based) radar data to reconstruct and forecast nonlinear wavefields. The model predictions are compared with the radar data not used in reconstruction, and the effect of wave spreading angle on radar measurements and wave forecasting performance is studied.

- We cross-validate radar-based forecasted wavefields with independent ATM and buoy measurements inside or outside the radar domains

- We study nonlinear wave statistics and large wave events based on forecasted large wavefields using (hybrid point and whole-area) Hi-Res measurements

* **Investigation of rogue wave events in cross seas:** We apply large-scale HPC-based SNOW simulations to study the characteristics of rogue wave events and statistics of rogue waves in cross seas. In particular, we focus on the understanding of the coupling effect of swell and wind waves upon the development of rogue waves.

RESULTS

To assess the performance of wave measurements and model predictions, direct comparisons between wave model predictions and HiRes 2010 field measurements are obtained. The comparisons indicate that phase-resolved reconstruction and forecasting of realistic ocean wavefields can be achieved by our wave prediction model and non-coherence marine radar sensed wave data. The resolution of the reconstructed and forecasted wavefield depends critically on the accuracy of sensed wave data, which is largely affected by radar-data inversion algorithm and the platform motion. Based on the reconstructed and forecasted large-scale wavefields, our study shows that it is of importance to include nonlinear effects in wavefield evolution for accurately predicting the temporal-spatial information of rogue waves and nonlinear wave statistics.

As illustration, we present two sample results on the comparisons of radar-based wave prediction with independent buoy and ATM measurements. These results demonstrate the effectiveness of the developed capability for phase-resolved reconstruction and prediction of realistic ocean waves based on radar sensed wave data.

(1) Prediction Based on Radar Data verse Datawell Buoy Measurement

To address the key question of whether a phase-resolved wave prediction can be achieved using radar data, we compare the reconstructed and forecasted wavefield to the independent buoy measurement. For this purpose, we use the HiRes measurements on June 18, 2010, in which radar data, buoy data and ATM data are all available. The positions of radar sensed data, ATM data, and buoy data in the large reconstructed wavefield domain are shown in figure 1.

Based on radar sensed wave data, we reconstruct a phase-resolved nonlinear wavefield and compare it to the independent buoy data in both the time history of the wave elevation and the wave spectrum. The comparisons are shown in figure 2. The comparison shows that for the wave spectrum, the agreement between the radar-data-based prediction and the buoy measurement is very well. The predicted time-variation of the wave elevation has a ~45% correlation with the buoy measurement.

(2) Prediction Based on Radar Data verse ATM Measurement

Figure 2 shows the direct comparisons between the reconstructed wavefield based on radar-sensed data with the independent ATM measurement. For the wave spectrum, the radar-data-based prediction again agrees very well with the independent ATM measurement. For the phase-resolved sea surface, the nonlinear phase-resolved prediction (based on radar data) achieves a ~55% correlation with the ATM measurement.

IMPACT/APPLICATIONS

Advances in large-scale nonlinear wave simulations and ocean wave sensing have recently made it possible to obtain phase-resolved high-resolution reconstruction and forecast of nonlinear ocean wavefields based on direct sensing of the waves. Such a capability will significantly improve ocean-surface sensing measurements and deployment, and data assimilation and interpretation, by providing a comprehensive wave-resolved computational framework. Another important potential application of this is to greatly increase the operational envelopes and survivability of naval ships by integration of such capability with ship-motion prediction and control tools.

REFERENCES

1. Wu, G. 2004 Direct simulation and deterministic prediction of large-scale nonlinear ocean wave-field. Ph.D Thesis, Massachusetts Institute of Technology, Cambridge, MA.
2. Yue, D.K.P. 2008 Nonlinear Wave Environments for Ship Motion Analysis, *27th Symposium on Naval Hydrodynamics*, October 5 – October 10, 2008, Seoul, Korea

PUBLICATIONS

1. Xiao, W., Henry, L., Liu, Y., Hendrickson, K. & Yue, D.K.P. "Ocean Wave Prediction Using Large-Scale Phase-Resolved Computations", Proceedings of the DoD HPCMP Users Group Conference 2008, June, Seattle, WA [published].
2. Yue, D.K.P. 2008 Nonlinear Wave Environments for Ship Motion Analysis, *27th Symposium on Naval Hydrodynamics*, October 5 – October 10, 2008, Seoul, Korea [published].
3. Xiao, W., Liu, Y. and Yue, D.K.P. 2009 Ocean Wave Prediction Using Large-Scale Phase-Resolved Computations, *Proceedings of the DoD HPCMP Users Group Conference* 2009, June, San Diego, CA [published]
4. Xiao, W., Liu, Y. and Yue, D.K.P. 2010 Large-Scale Deterministic Predictions of Nonlinear Ocean Wave-Fields, *Proceedings of the DoD HPCMP Users Group Conference* 2010, June, Chicago, IL [published]
5. Tao, A. & Liu, Y. 2010 Rogue Waves Due To Nonlinear Broadband Wave Interactions, *Proc. 25th International Workshop on Water Waves and Floating Bodies,* May 9-12, Harbin, China [published, refereed]
6. Alam, M.-R., Liu, Y. and Yue, D.K.P. 2010 Oblique sub- and super-harmonic Bragg resonance of surface waves by bottom ripples. *Journal of Fluid Mechanics*, **643**: 437-447 [published, refereed]

7. Alam, M.-R., Liu, Y. and Yue, D.K.P. 2011 Nonlinear wave signature of and oscillating and translating disturbance in two-layer fluid. *Journal of Fluid Mechanics*, **675**: 477–494 [published].
8. Xiao, W., Liu, Y. and Yue, D.K.P. 2011a Nonlinear nearshore wave environment for ship motion. Proceedings of 11th International Conference on Fast Sea Transportation, FAST 2011, Honolulu, Hawaii, USA [published, refereed].
9. Xiao, W., Liu, Y. and Yue, D.K.P. 2011b Large-Scale Deterministic Predictions of Nonlinear Ocean Wave-Fields, *Proceedings of the DoD HPCMP Users Group Conference* 2011, June, Portland, OR [published]
10. Yan, H. & Liu, Y. 2011a An efficient high-order boundary element method for nonlinear wave-wave and wave-body interactions. *Journal of Computational Physics* **230**, pp. 402-424 [published, refereed].
11. Yan, H. & Liu, Y. 2011b Nonlinear computation of water impact of axisymmetric bodies. *Journal of Ship Research*, Vol. 55, No. 1, pp. 29-44 [published, refereed].
12. Xiao, W., Liu, Y. and Yue, D.K.P. 2012 Prediction of Rogue Waves by Large-Scale Phase-Resolved Nonlinear Wavefield Simulations, *Proceedings of the DoD HPCMP Users Group Conference* 2012, New Orleans, LA [published].
13. Xiao, W.; Liu, Y.; Wu, G. & Yue, D.K.P. 2013 Rogue wave occurrence and dynamics by direct simulations of nonlinear wavefield evolution, *Journal of Fluid Mechanics* [In press, refereed].

STUDENTS GRADUATED

3 PhD students (2 females)

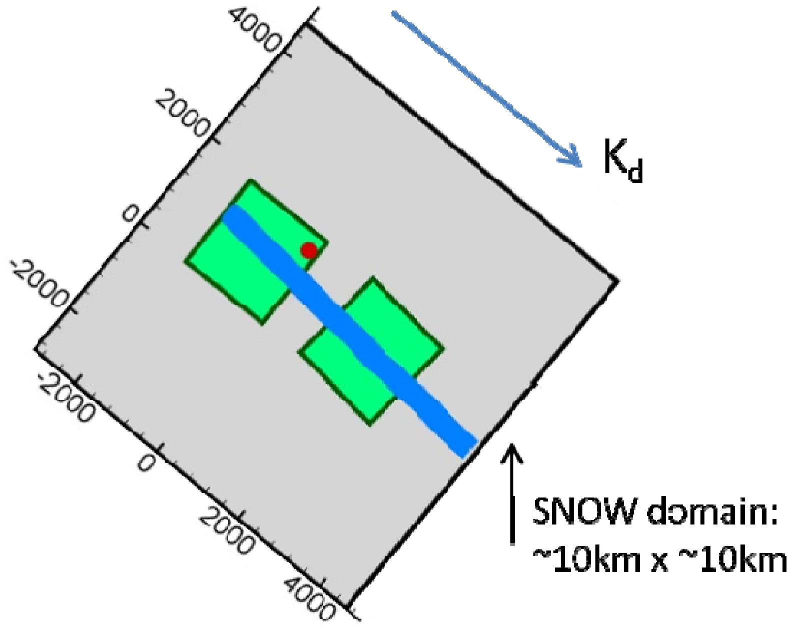

Figure 1. Wavefield reconstruction and forecasting in a domain of ~10 km × 10 km, using ONR HiRes wave measurements on June 18, 2010. The regions sensed by FLIP-based radars and ATM and the location of the Datawell buoys are indicated: radar data (green regions), ATM data (blue strip), and buoy data (red spot). The dominant wave propagation direction is along the direction of K_d. The sea state has a significant wave height of H_s = ~3.3 m, a peak wave period of T_p = ~9.5 s, and a width of directional spreading angle of Θ = ~80°.

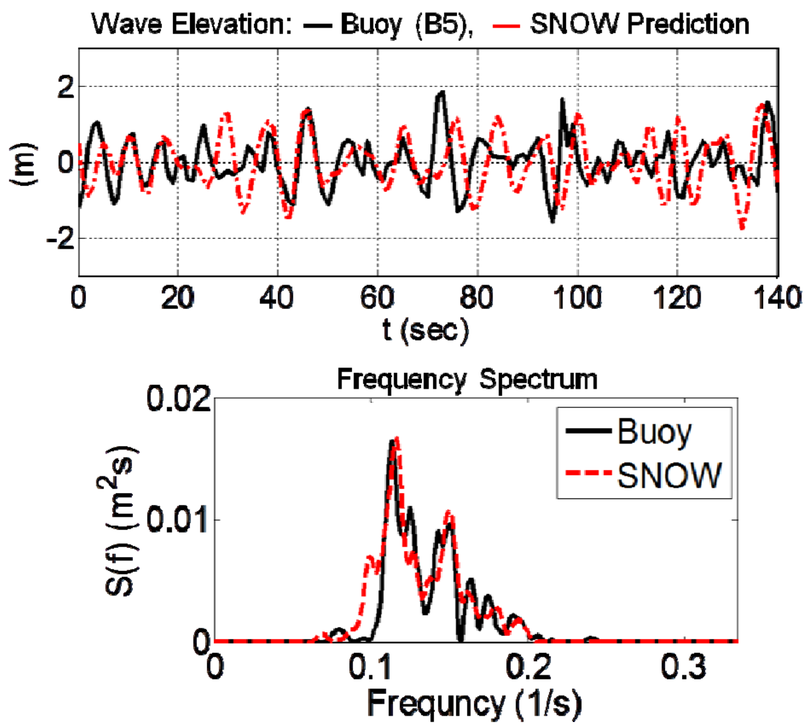

Figure 2. Comparison of phased-resolved reconstructed wavefield based on radar data with the independent buoy measurement. Top panel: comparison of the time-variation of the wave elevation; and bottom panel: comparison of the wave spectrum of the sea.

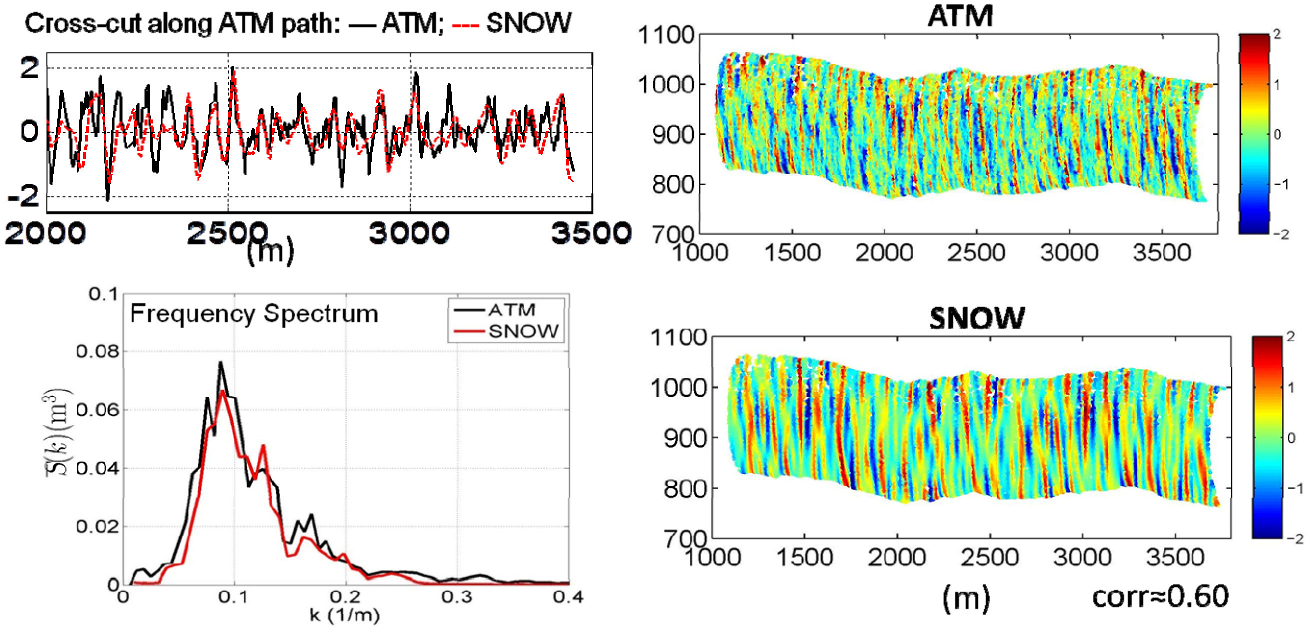

Figure 3. Comparison of phased-resolved reconstructed wavefield based on radar data with the independent ATM measurement. Right panels: comparison of the composite wave elevation between ATM measurement and the radar-data-based prediction. Top left panel: comparison of the cross-cut wave elevation along ATM path. Bottom left panel: comparison of the wave spectrum of the sea.